CAVITATION CHARACTERISTICS OF A
HIGH RAMP ANGLE WATER-JET INLET

by

JEROME J. FEE

THESIS SUPERVISOR
E.S. TAYLOR

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JEROME J. FEE
LT. U.S. NAVY

B.S., U.S. NAVAL ACADEMY
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Signature of Author...
Department of Naval Architecture and
Marine Engineering, May 19, 1967

Certified by...
Thesis Supervisor

Certified by...
Reader for Department

Accepted by...
Chairman, Departmental Committee on Graduate Students

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ABSTRACT

An investigation was made in a water tunnel of the cavitation characteristics of a flush water-jet inlet with a 14.5 degree ramp angle. Results of this investigation were compared to extrapolated wind tunnel test data. The wind tunnel data indicated that a ramp angle of over 7 degrees would probably cavitate if used on a high speed surface effect ship. It was found that the pressure distribution from the water tunnel tests was not as severe as that predicted by wind tunnel data. Consequently, ramp angles steeper than 7 degrees can probably be used.

THESIS SUPERVISOR: E. S. TAYLOR
TITLE: PROFESSOR OF FLIGHT ENGINEERING

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Also, I should like to thank Mr. Christensen for his help in construction of the test apparatus.

LIST OF FIGURES

LIST OF SYMBOLS

A	flow area (ft.^{2})
$(Cp)_{max}$	maximum pressure coef.
Cv	velocity coef.
d	flow diameter (in.)
I	orifice constant
P	pressure (lbs/ft^2) ("Hg) ("H_2O)
ΔP	pressure differential (lbs/ft^2) ("Hg) ("H_2O)
Q	flow rate (ft.^{3}/hr) (ft.^{3}/sec)
R	ram recovery ratio
T	Thrust (lbf)
T	Temperature (^oF)
V	Velocity (ft/sec) (ft/hr)
ΔV	velocity differential (ft/sec)
η	efficiency
ρ	density lbm/ft^3
γ	density lbf/ft^3

SUBSCRIPTS

i	inlet
j	jet
m	main stream
o	free stream
1	pressure tap 1
2	pressure tap 2

CAVITATION CHARACTERISTICS OF A HIGH RAMP ANGLE FLUSH WATER-JET INLET

1. INTRODUCTION

The object of this thesis was to investigate the pressure distribution on a flush water-jet inlet with a 14.5 degree ramp angle, and the variables which affect this pressure distribution. The results of this investigation were then applied to a five hundred ton captured air bubble craft* in order to investigate its cavitation characteristics.

The background of water-jets, and a detailed discussion of why they have suddenly become important as a means of propulsion is contained in Appendix A.

Little is known about large water-jet systems. They have been used in various small craft of under ten tons, but no large water-jet units have been used to propel anything close to five hundred tons. The United States Navy's experimental destroyer Witek employs two Kort nozzle propellers of 30,000 horsepower each which are in some respects similar to water-jets, but the problems of design and operation differ substantially from actual water-jets.

Boeing is currently building a 58 ton hydrofoil craft which will be powered by a 3100 horsepower water-jet unit (12). A Lockheed optimiaztion study indicated they should use a centrifugal pump with a

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*Referred to as C.A.B., it is similar to a hovercraft but has side walls projecting below the water surface to retard the loss of air from the craft's air cushion.

ram inlet. The same studies indicated that a flush inlet with axial pumps would be superior for a displacement or C.A.B. hull (7). The data used in arriving at this decision came mainly from Mossman and Randall's wind tunnel tests (8). These tests were made in 1947 using an Ames 36 inch wind tunnel and flush inlets suitable for use as intakes for jet engines on aircraft. Though this data has been invaluable in preliminary studies of flush water-jet inlets, it is in no way sufficient for final design decisions. Based on these studies, water-jets with very shallow ramp angles are favored, since they have low values of (Cp)max (7).

Extensive work remains to be done in finding the optimum inlet for minimum drag, maximum pressure recovery, proper boundary layer ingestion, and most important, avoidance of cavitation. At this point there is almost no water tunnel data available for water-jet inlets. Subsequently, it is important to investigate ways of obtaining this data, and in particular, to study cavitation properties of these inlets.

Mossman and Randall investigated inlets with ramp angles of 5, 7, 9, and $11\frac{1}{2}$ degrees (8). It has been concluded that the optimum inlet for most purposes is 7 degrees (7) (8). However, a ramp of 7 degrees installed as part of a propulsion system in a ship, would cause extensive problems in internal arrangement. For a 7 degree ramp to rise ten feet, from the ship's bottom to the main pumps, would require more than eighty feet of ship's length and would carry about 130 tons of sea water in developing 150,000 shaft horsepower (6). Since a higher ramp angle would reduce the length, duct losses, and weight of the system, the inlet characteristics of these ramps should be investigated.

2. PROCEDURE

A detailed description of apparatus and procedures is contained in Appendix B. Briefly, the pressure distribution across a 14.5 degree inlet to a one-half inch water-jet was obtained for different values of free stream velocity (Vo), free stream pressure (Po), water-jet inlet velocity (Vi), and boundary layer thickness. This data obtained from the water tunnel was plotted as a minimum non-dimensional pressure

$$C_{P_{MAX}} = \frac{P_o - P_{MIN}}{\frac{1}{2}\rho V_o^2} \tag{3}$$

against a non-dimensional water-jet inlet velocity

$$C_V = V_i / V_o \tag{4}$$

This data was then compared to wind tunnel data from reference (8).

3. RESULTS

The results are summarized in Figure III expressed in terms of (Cp)max and Cv as defined in equations (3) and (4). The two solid lines represent the results obtained with and without increased boundary layer as labeled. The points marked with "X" represent the wind tunnel results obtained by Mossman and Randall using ramp angles of 5, 7, 9, and 11.5 degrees with Cv equal to 0.6 (8). The points marked "*" indicate the extreme range of values expected for a 14.5 degree inlet, as extrapolated from Figure IV.

Cavitation was observed on a few occasions at the lowest free stream pressures and highest free stream velocities. It always occurred about 0.05 inches aft of pressure tap (1), which was 0.15 inches aft of the ramp entrance. In each of these events, the pressure at this tap indicted at least five inches of mercury absolute or above. This is well above vapor pressure.

The resulting values of (Cp)max were substantially below the mid-point of the extrapolated range for the 14.5 degree inlet from Figure IV, and showed a definite linear dependence on Cv. Increasing the boundary layer caused an approximately uniform decrease in (Cp)max for all values of Cv. Sample results are shown in Appendix C. Sample calculations are listed under Appendix D.

The limitations of the apparatus used did not permit free stream velocities of above seven feet per second and water-jet inlet velocities of above four feet per second. The resulting range of Cv was from about 0.1 to 0.6. If conditions had permitted it would have been desirable to

obtain values of Cv up to 1.0. Additionally, it was not possible to evacuate the system pressure to below five inches of mercury absolute, which made it impossible to obtain the same cavitation numbers that would be expected on a full size craft. However, the pressure distribution obtained readily lends itself to a cavitation study.

4. DISCUSSION OF RESULTS

The most significant results of this experiment were the generally low values of (Cp)max, and the dependence of (Cp)max upon Cv.

Examination of the pressure coefficients obtained in wind tunnel tests for shallow ramp angle inlets yields a non-linear dependence between (Cp)max and ramp angle as shown in Figure IV. Extending this relationship to an inlet with a 14.5 degree ramp angle, a (Cp)max between 0.45 and 0.56 is obtained at a Cv of 0.6. This compares to a value of 0.42 found in the water tunnel tests. This difference can be partly attributed to different boundary layer conditions between the air tunnel and water tunnel tests. Mossman and Randall indicated that they had difficulty in controlling the boundary layer in their tests; however, they did make every effort to minimize the boundary layer. Minimum boundary layer at the inlet is important in aircraft design in order to maximize ram recovery (7). On the other hand, increased boundary layer ingestion in water-jets is desirable for thrust augmentation, and possibly in the suppression of cavitation.

In the water tunnel there was no means available for measurement of the boundary layer, and time did not permit modification of the equipment to accomplish such measurements. However, it was possible to increase the boundary layer by some arbitrary amount, by replacing the upper surface of the test section with a silicon paper coating. This reduced (Cp)max from 0.42 to 0.36, demonstrating the rather strong dependence of (Cp)max on boundary layer thickness.

Since cavitation was observed just aft of pressure tap (1), while the pressure at the tap was indicated to be five inches of mercury, it is possible that the pressure tap was not at the point of minimum pressure. This would account for the low values of (Cp)max; however, any slight protrusion of the trailing edge of the pressure tap from the ramp wall could cause early inception of cavitation. Despite extensive filing to make this area smooth, a small discontinuity of the surface still existed. Additionally, occasional aeration and impurities in the flow were noticed which could provoke early cavitation in this area.

The manometer used for measuring the pressure difference, $P_o - P_1$, could be read only to the nearest 0.1 inches of oil (S.G. 2.95). This could result in errors of (Cp)max as high as ten percent in a range of Cv between 0.5 and 0.6. The accuracy of the pressure readings accounts for the scatter of some of the data; however, it probably did not appreciably affect the mean value line of (Cp)max shown in Figure III.

Finally, in all experiments of this sort, similar to conduit flow, it has been found that formal verification of ideal fluid theory is not expected (11). As applied to the tests, the lower the Reynolds' number the more the experimental results are expected to depart from ideal fluid theory. In the water tunnel, Reynolds' numbers were on the order of $3\times10^{+4}$. Since the Reynolds' numbers in the wind tunnel tests were on the order of $3\times10^{+6}$, the (Cp)max obtained from the water tunnel should be lower than those obtained from the wind tunnel.

The results of the tests by Mossman and Randall showed constant values of (Cp)max for a given ramp angle with no dependence on Cv (8). The water tunnel results disagree with this point. The contradiction is

probably the result of the difference in geometry between the inlet used by Mossman and Randall and the inlet used in the water tunnel (Figures VIII and IX).

The point of minimum pressure on the inlet used in the wind tunnel occurred at a point such that it was mainly dependent on free stream velocity (Figure VIII). Whereas, the water-jet inlet showed a slightly different flow pattern with the point of minimum pressure occurring at a point that was dependent on inlet velocity (Figure IX).

Keeping in mind the above discussion concerning the accuracy of the data obtained from the water tunnel, the results of these tests indicate further investigation of the 14.5 degree inlet is warranted. Since the physical design of the hydrofoil craft lends itself to a ram type inlet (7), the major application of the type of inlet tested would be to the captured air bubble craft.

The maximum designed speed for a five hundred ton C.A.B. is expected to be 65 knots. The water-jet inlet is planned to be about six feet below the water surface (Figure X), yielding a Po of 2500 lbs/ft^2. At Cv equal to 0.6, (Cp)max for the 11.5 and 14.5 degree inlets obtained from Figure IV is 0.27 and 0.45 respectively. The (Cp)max in eighty degree water, above which cavitation is expected to occur, on the five hundred ton C.A.B. is 0.21 in the cruise condition. This would indicate that cavitation would occur at the entrance to the ramp on both the 11.5 and 14.5 degree inlets. As previously noted, (Cp)max was not 0.45, as indicated in Figure IV, but 0.42. This was further decreased to 0.36, by increasing the boundary layer.

In addition, considering the variation of (Cp)max with Cv

as shown in Figure III, reduction in Cv would further increase the cavitation performance, at least making the 11.5 degree inlet feasible, and possibly even making the 14.5 degree inlet feasible. Cavitation performance could also be improved by the use of a better designed inlet.

The possibility of going to higher ramp angles not only would greatly facilitate the internal arrangements in way of the machinery spaces, but would result in shortend ducts accompanied by reductions in duct losses. Therefore, the highest ramp angle consistent with subcavitation criteria should be used in water-jet design.

This discussion has concentrated on cavitation of the inlet to the ramp; however, cavitation is a problem at two other key areas in a water-jet system. One is the cavitation of the main jet pump, and the other is the lip of the inlet (Figure II). The cavitation of the pump is mainly dependent on ram recovery and flow diffusion, with little relationship to this discussion (3). The cavitation of the lip is independent of ramp angle, but it is affected by Cv. During cruise operation, when Cv is greater than 1.0, cavitation is most likely to occur on the external side of the lip, resulting in little disturbance to the flow in the inlet (7). In the take-off condition, where Cv is greater than 1.0, cavitation could possibly occur on the inside of the lip. In this case $(C_p)_{max}$ must be in the vicinity of 1.0 for cavitation to begin. Therefore, the problem of lip cavitation does not appear as critical as ramp inlet cavitation.

5. CONCLUSIONS

A. (Cp)max is below that predicted by wind tunnel data.

B. (Cp)max is dependent on boundary layer thickness, further reducing (Cp)max below wind tunnel data.

C. (Cp)max appears to have a dependence on Cv, but more investigation is required to verify this fact.

D. The results of this experiment are based upon data of only marginal accuracy, due to the unavailability of a large water tunnel with its associated instrumentation*. Due to this fact, no water-jet design decisions can be made solely as a result of this investigation.

E. Though wind tunnel data indicates that a 11.5 degree ramp angle is unsatisfactory for a five hundred ton C.A.B., water tunnel data may show it will be acceptable.

F. The 14.5 degree ramp angle inlet is probably too cavitation-limited to be used on a five hundred ton C.A.B., but further investigations should be made.

G. It is very doubtful that an inlet with more than a 14.5 degree ramp angle could be used on a large C.A.B. of five hundred tons or more, without severe cavitation.

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*The M.I.T. propeller tunnel would have been ideal for this experiment but it was inoperative due to significant modification from the spring of 1966 to the fall of 1967.

6. RECOMMENDATIONS

As soon as the propeller tunnel at M.I.T. (Figure V) is back in operation, the investigation of water-jet inlets should be repeated on a larger scale. It is recommended that these tests should concentrate on the 11.5 degree inlet, for which some wind tunnel data is available. The following points are considered of paramount importance:

A. The water-jet should be designed with a two inch diameter, as shown in Figure VI.

B. It should be housed in a model sidewall, as shown in Figure VII.* The top of the sidewall should be attached to a piece that can serve as the top of the propeller tunnel test section. The entire device then could be placed in the propeller tunnel test section through the top.

C. A minimum of twelve static pressure taps should be placed as shown in Figure VI. This would ensure an adequate plot of pressure distribution along the ramp.

D. A series of stream probes should be used for measuring boundary layer thickness and ram recovery factor (R). Provisions should be made for variation of boundary layer.

E. Cv should be varied between 0.6 to 0.8 and 1.2 to 1.6, since these are the prime areas of interest for cruise and take-off operation, respectively.

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*The sidewall does not have to be an exact model of a C.A.B. sidewall. Any general hull form will suffice.

F. If time permits, further investigation of the 14.5 degree inlet, or some intermediate angle between 11.5 and 14.5 degrees would be advisable. Also, investigation of a square shaped inlet which would take maximum advantage of boundary layer ingestion could prove of great value.

G. In a search of the available literature no potential flow solution was found for water-jet inlets. Avis Borden of D.T.M.B. has produced a potential flow solution for scoop inlets of condensers (13). Though this solution is not directly applicable to a flush water-jet inlet, it forms a basis for an approach to the problem. A joint thesis with one person developing a potential flow solution, while the other carries out the recommended experimental work would produce a most useful thesis. The use of a square or rectangular shaped inlet would greatly facilitate the creation of a potential flow solution around the inlet. The solution could be obtained using a two dimensional flow model on a computer.

APPENDIX

APPENDIX A

SUPPLEMENTARY BACKGROUND INFORMATION

Water-jet propulsion of ships dates back to the earliest days of steamships. In fact, James Rumsay operated a steam powered, water-jet propelled boat on the Potomac River in 1787, twenty years before the construction of Robert Fulton's famed Clermont. Rumsay died in 1793, and with him water-jet propulsion temporarily died (1) (2).

In a seaway the efficiency of water-jets compared favorably with the early paddle wheel propulsion systems, and might have come into wide usage had Rumsay lived longer. However, water-jets could not have competed in efficiency with the Ericsson Propeller of 1840, and would have suffered the same fate as the paddle wheel.

The principle of water-jet propulsion is a simple one. Water is drawn into the hull and transported by a duct or pipe to a large pump. The pump imparts momentum by an increase in velocity to the flow which is exhausted out the stern. The thrust developed by the water-jet is

$$T = \rho Q \Delta V \qquad (1)$$

The ideal efficiency of this water-jet is

$$\eta = \frac{2}{2 + \Delta V / V} \qquad (2)$$

where V is the speed of the craft through the water, and ΔV the increment in velocity of the flow provided by the water-jet (3).

Thus, one of the disadvantages of the water-jet becomes immediately apparent. For high efficiency, ΔV must be small, and V must be large. But for high speed, ship drag is high, requiring a large amount of thrust. Since ΔV must be small for efficient operation, the flow rate, Q, must be very high; this large volume of water is effectively being carried along within the ship, resulting in extensive extra weight. This is not true for the screw propeller. Additionally, the water-jet has high inlet and ducting losses, while in a screw propeller losses of this sort are minimal (4). These facts alone provide ample justification for screw propellers versus water-jets for marine propulsion.

The problems of marine propulsion are changing with the development of surface effect ships (GEM's, CAB's, hovercraft, etc.) and high speed hydrofoil craft, with interest shifting to the forty to one hundred knot speed range. In this range, the normal screw propeller looses its high efficiency due to severe cavitation, encountered even at the lowest end of this speed range. Supercavitating propellers, specially designed to operate in the cavitating condition, demonstrate good efficiency, but for use in large ships, they are limited by structural strength problems (3). A list of additional problems associated with the use of supercavitating propellers may be found in reference (4).

Air screw propulsion is currently being used on all hovercraft vehicles. Since these vehicles have no projections below the water's surface, the air propeller has a definite advantage over both the water-jet and the water screw propeller. Furthermore, the air propeller exhibits good propulsive efficiency, with a reasonable blade

area for craft of under five hundred tons (5) (6). However, above five hundred tons, powering considerations indicate that a captured air bubble craft is superior to a hovercraft for most applications. Though captured air bubble craft of five hundred tons and above have not yet been built, the surface penetrating side walls and the prohibitavely large number of air propellers, that would be required to obtain a reasonable efficiency appear to favor the use of water-jets, or super-cavitating water propellers.

The United States Navy is about to undertake a ten year program leading to the design and development of a four thousand ton captured air bubble type surface effect ship. The Navy will first construct three five hundred ton ships of one-half lineal scale, in order to form the technological capability for constructing a four thousand ton ship. One of the five hundred ton ships will be propelled by water jets, one by supercavitating water propellers, and one by air propellers. The latter is the largest craft presently envisioned to use air propellers (5).

APPENDIX B

DETAILS OF PROCEDURE AND DESCRIPTION OF APPARATUS

The water tunnel used for conducting this investigation was originally designed to test axial inducers (9). It has a capacity of 28 gallons and was modified for these tests to have a square, parallel-walled test section 1.5 inches on a side and 18 inches long. The piping and valves were three inches in diameter and were constructed of aluminum (Figure I). On the top of the test section a one-half inch diameter water-jet inlet was installed (Figure II). The flow from the inlet was carried by one-half inch O.D. copper tubing leading to a 1.5 horsepower centrifigul pump twenty feet below the test section. The jet flow was returned to the main circulating flow on the exhaust side of the main circulating pump. The main circulating pump has a peak capacity of five hundred gallons per minute. The main flow was measured by a 0.748 inch square-edged orifice, while the flow from the inlet was measured by a 0.127 inch square-edged orifice. The flow was measured in accordance with reference (10). Three pressure taps were located as shown in Figure II. Pressure taps (0) and (2) were run to a mercury manometer and measured against atmospheric pressure, while pressure tap (1) was run to a meriam oil manometer (S.G. 2.95), measured the pressure differential between pressure tap (0) and pressure tap (1).

The main circulating flow was varied by regulating the main circulating pump by-pass valve (Figure I), resulting in variation of the free stream velocity between three and seven feet per second. The flow

in the water-jet was regulated by a clip attached to a flexible piece of tubing, through which the flow from the inlet passed (Figure I). In this manner the flow was regulated between zero and four feet per second.

Before each series of runs, the water in the tunnel was passed through a filter (Figure I) to remove impurities. Additionally, the system was evacuated and allowed to settle in order to reduce the aeration, thus minimizing premature cavitation inception.

Each pressure tap line was installed with a T-fitting at its highest point in order to vent the lines of all air bubbles before each series of runs.

The water-jet inlet was constructed by drilling a one-half inch diameter hole in the top of the plexiglass test section at 14.5° from the horizontal (±0.2 degrees). The resulting hole had parallel walls, and the inlet had a width to depth ratio of four (Figure II), similar to the inlets tested in reference (8).

The system was connected through the top of its plenum to a series of three steam ejectors. This enabled evacuation of the system for deaeration and operating below ambient free stream pressure when desired. The maximum vacuum obtainable was five inches of mercury absolute.

Prior to each data sample the desired free stream flow was obtained by adjusting the throttle and by-pass valves. The desired flow through the water-jet was produced by adjusting the clip valve. The system required approximately three minutes to reach steady state. Each basic set of runs involved constant free stream flow and free

stream pressure, while varying the jet velocity from its maximum to its minimum. The highest obtainable value of Cv was 0.8. Velocity ratios above this value are above the optimum range for water-jets due to a decreasing ram recovery ratio (8). After each set of runs, the pumps were stopped while the system was deaerated and pressure taps vented. The succeeding sets of runs were made, varying either free stream flow or pressure and repeating the above procedure.

Several operating conditions were later duplicated with an increased boundry layer at the inlet by covering the smooth plexiglass surface with a rougher silicon surface.

In addition to the various pressure readings made on each run, the inlet was inspected for visual signs of cavitation.

Extreme accuracy was required in measuring the pressure differential between tap (0) and tap (1). An error of 0.01 pounds per square inch could result in an error of ten percent in the calculated value of (Cp)max. More than one hundred sets of data were taken, but many of the early readings were rejected because of erronious values caused by occasional air bubbles entrapped in the lines between the pressure taps and the manometers.

APPENDIX C

SAMPLE DATA

A sample of the data taken is shown below. Additionally, calculated values of Vo, Vi, Cv, and (Cp)max are given in the last four columns. Runs 40 through 50 were for normal boundary layer thickness and 51 through 55 are for increased boundary layer.

	°F To	"Hg Po	"Oil Po-P1	"Hg P2	"Hg ▲Pm	"Hg ▲Pj	Ft/Sec Vo	Ft/Sec Vi	Cv	(Cp)max
40	92	4.0	0.5	3.5	17.1	19.1	4.6	2.7	0.59	0.37
41	93	8.0	0.7	8.4	21.0	23.2	5.1	2.9	0.57	0.41
42	95	9.5	0.5	9.5	22.1	8.4	5.2	1.7	0.33	0.28
43	96	13.8	0.9	13.5	28.3	27.2	5.9	3.2	0.54	0.40
44	96	14.0	0.75	13.8	28.2	12.1	5.9	2.2	0.37	0.33
45	97	19.0	1.1	19.0	39.0	30.9	6.9	3.5	0.51	0.36
46	98	19.0	1.0	19.0	39.8	15.3	7.0	2.4	0.34	0.32
47	99	2.0	0.5	1.5	15.9	2.7	4.5	1.1	0.24	0.38
48	100	2.0	0.3	2.0	16.1	0.5	4.5	0.4	0.09	0.24
49	100	5.0	0.7	4.8	25.2	2.7	5.6	1.1	0.20	0.34
50	102	6.0	0.5	5.5	26.0	1.0	5.7	0.6	0.11	0.25
51	69	9.3	0.35	9.1	18.0	2.7	4.7	1.0	0.21	0.24
52	75	9.8	0.20	9.3	25.9	2.5	5.9	1.0	0.17	0.09
53	84	13.3	0.60	13.6	16.9	35.5	4.6	3.7	0.80	0.44
54	84	28.3	1.0	28.2	34.9	40.0	6.6	4.0	0.60	0.35
55	85	28.3	0.7	28.2	35.0	10.1	6.6	2.0	0.30	0.25

APPENDIX D

SAMPLE CALCULATIONS

The calculations shown are for run 40. They are similar to those on all the other runs.

1. Convert ΔPm inches of water

$$17.1 \times 13.6 = 232''$$

2. Solve for flow rate (Ref. 10)

$$Q = I\, d^2 \sqrt{\Delta P / \rho} \qquad (5)$$

$$Q = 60 \times 2.25 \sqrt{\frac{232}{62.4}} = 261 \text{ ft}^3/\text{hr}$$

3. Solve for Vo

$$V = Q/A \qquad (6)$$

$$V = 261/.0156 = 16{,}700 \text{ ft/hr} = 4.63 \text{ ft/sec}$$

4. Covert ΔPj to inches of water

$$19.1 \times 13.6 = 260''$$

5. Solve for flow rate

$$Q = 25 \times .125 \sqrt{\frac{260}{62.4}} = 6.6 \text{ ft}^3/\text{hr}$$

6. Solve for Vj

$$Vj = 6.6/.00068 = 9800 \frac{\text{ft}}{\text{hr}} = 2.7 \text{ ft/sec}$$

7. Convert Po-Pl to lbs/ft^2

$$Po\text{-}Pl = \frac{0.5 \times 2.95}{12} \times 62.4 = 7.65 \text{ lbs/ft}^2$$

8. Calculate Cv

$$Cv = Vi/Vo \qquad (4)$$

$$Cv = 2.7/4.6 = 0.59$$

9. Calculate (Cp)max

$$(Cp)max = \frac{Po - P_1}{\frac{1}{2} PV_o^2} \qquad (3)$$

$$(Cp)max = \frac{7.65}{\frac{1}{2}\,\frac{62.4}{32.2}\,(4.6)^2} = 0.37$$

BIBLIOGRAPHY

1. Americana Corporation, "The Encyclopedia Americana", 1951.

2. Buller Company, "Water-Jets for Boat Propulsion", 1964.

3. Levy, J., "The Design of Water-Jet Propulsion Systems for Hydrofoil Craft", Marine Technology, Vol. 2, No. 1, 1965.

4. Johnson, V. E., "Water-Jet Propulsion for High Speed Hydrofoil Craft", AIAA Paper 64-306, 1964

5. Ford, A.G., "Proposed Technical Approach for Development of Large Surface Effect Ships", DTMB, 1965, (Unpublished).

6. Ford, A.G., Fee, J.J., "In House Computer Aided Design Feasibility Study of Surface Effect Ships", DTMB, 1966, (Unpublished).

7. Lockheed California and Company, "Water-Jet Propulsion System Study", LR 17885-5, 1965.

8. Mossman, E.A., Randall, L.M. "An Experimental Investigation of Design Variables for NACA Submerged Duct Entrances", NACA RM A7130, 1948.

9. Mullan, P.J., "An Investigation of Cavitating Inducers for Turbopumps", M.I.T. Thesis, 1959.

10. ASME Research Committee on Fluid Meters, "Flowmeter Computation Handbook", ASME, 1961.

11. Roberston, J. M., "Hydrodynamics in Theory and Application", Prentice Hall, 1965.

12. Stevens, D.L., Jr., "Design and Procurement of PGH", Department of the Navy, June 1966.

13. Borden, A., "Testing Main Injection Scoops and Overboard Discharges in Restricted Channels", D.T.M.B. Report 801, January, 1952.

FIGURE I

WATER TUNNEL

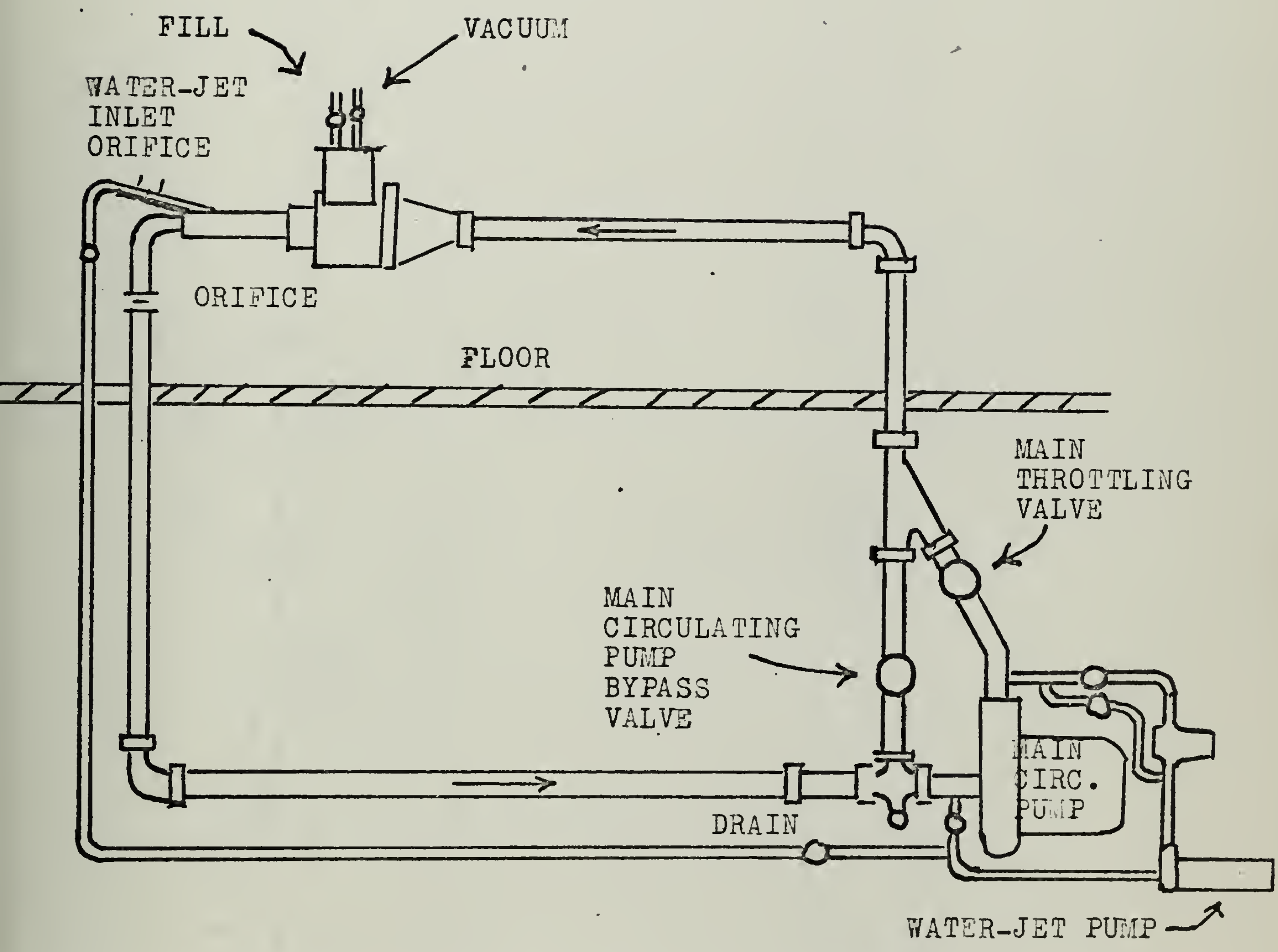
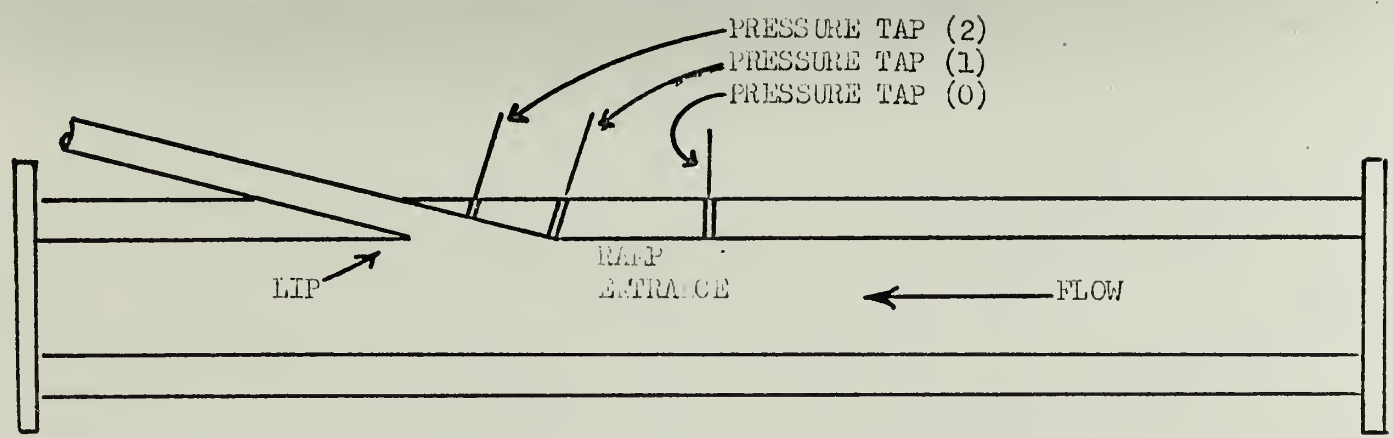
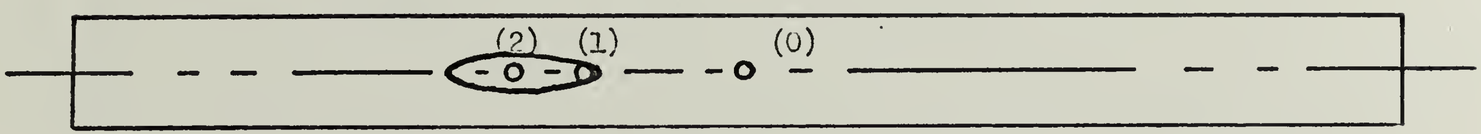


FIGURE II

WATER-JET TEST SECTION



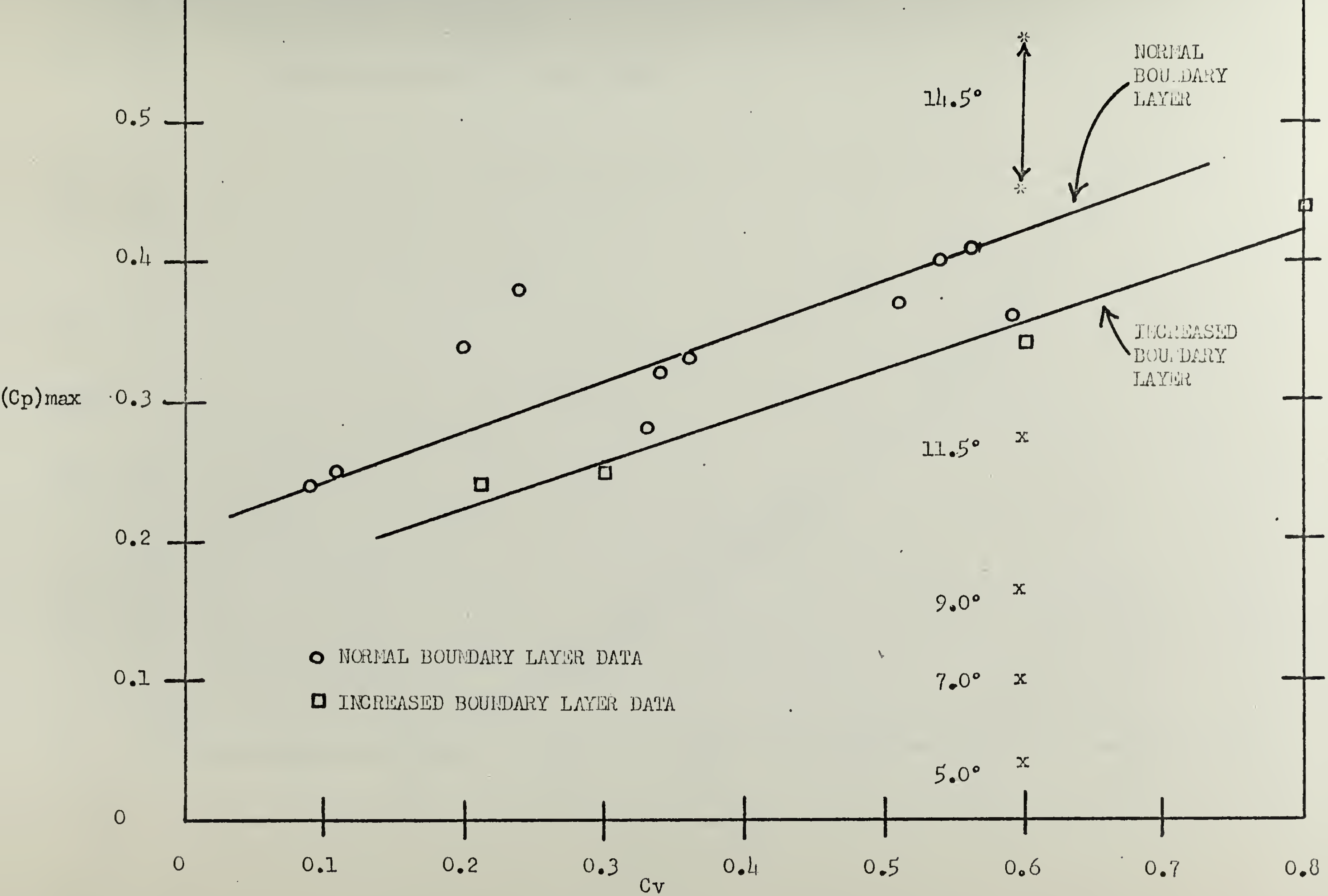
SIDE VIEW



TOP OF TEST SECTION

FIGURE III

PRESSURE COEFFICIENT VS VELOCITY COEFFICIENT



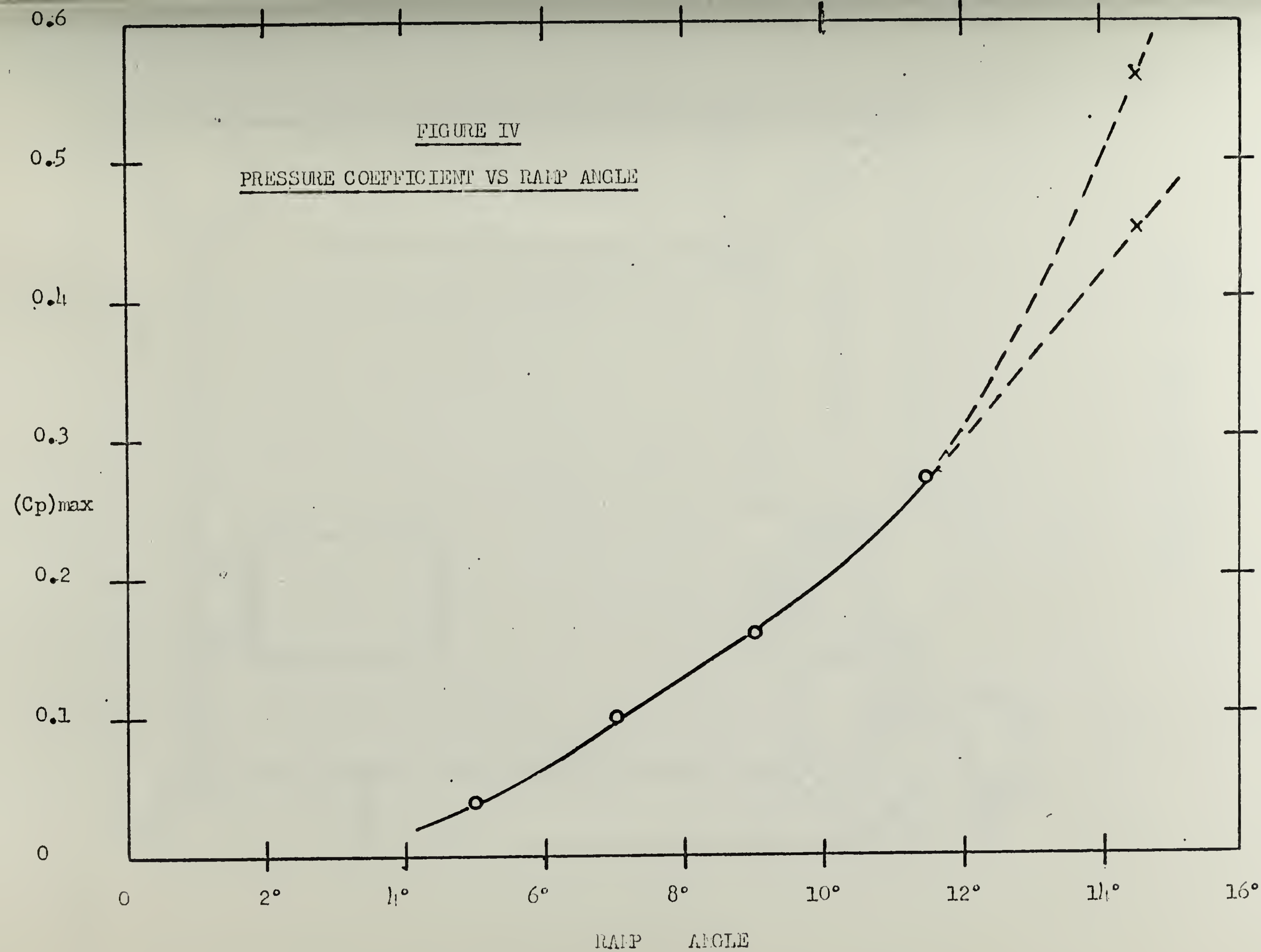


FIGURE IV
PRESSURE COEFFICIENT VS RAMP ANGLE
(Cp)max
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2°
4°
6°
8°
10°
12°
14°
16°
RAMP ANGLE

FIGURE V

M.I.T. PROPELLER TUNNEL

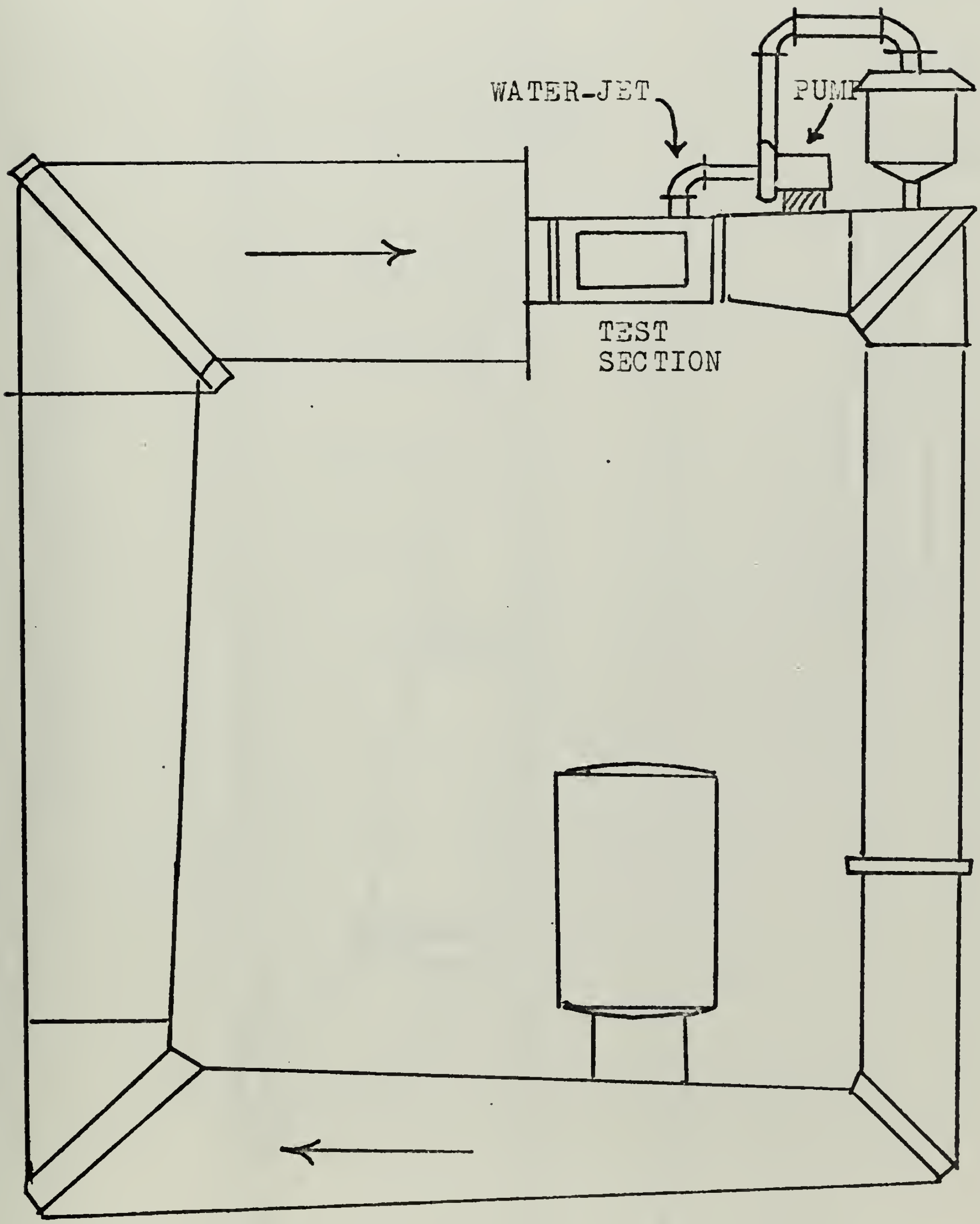


FIGURE VI

INSTRUMENTATION OF PROPOSED WATER-JET INLET

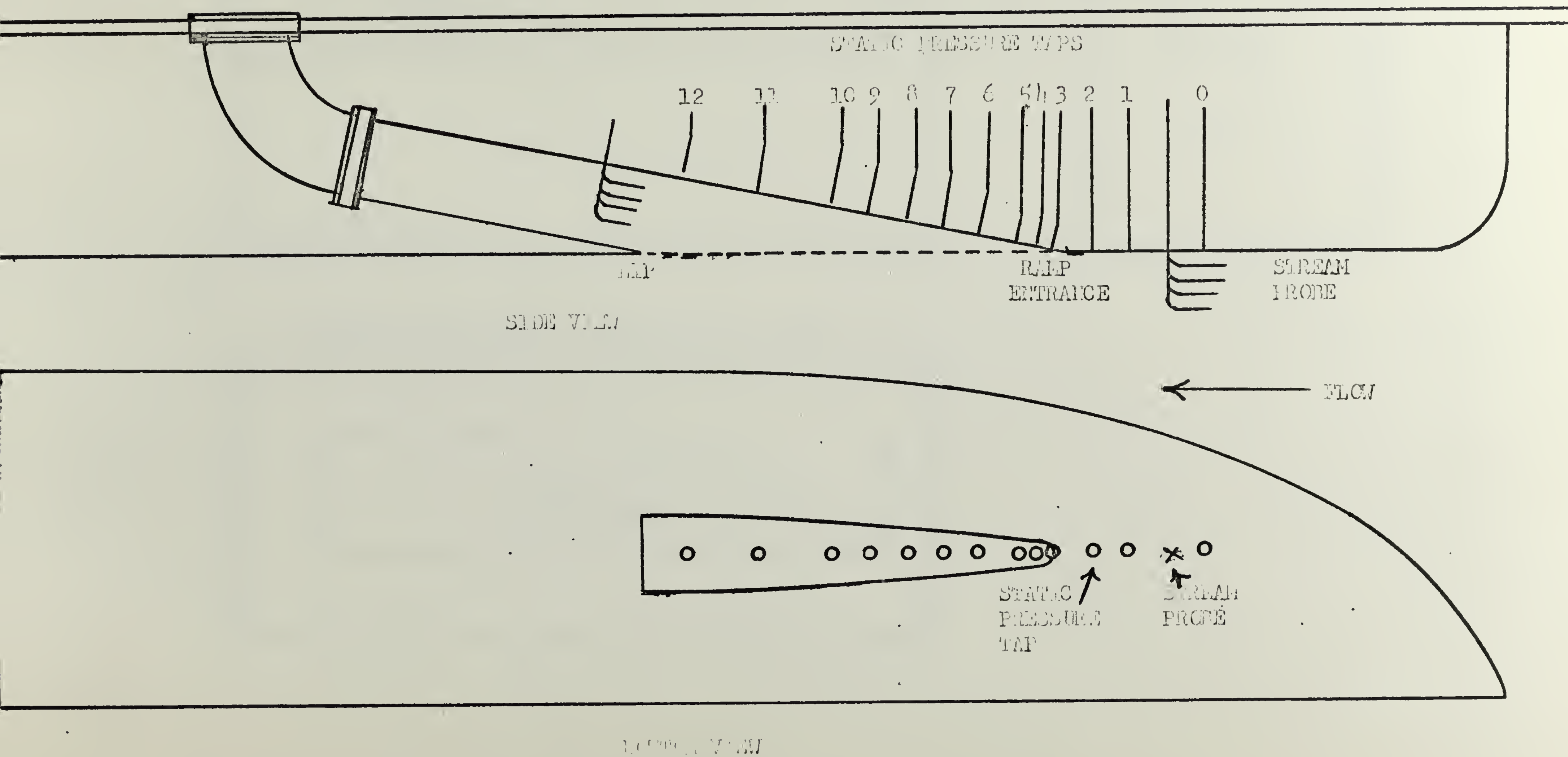


FIGURE VII

PROPELLER TUNNEL TEST SECTION

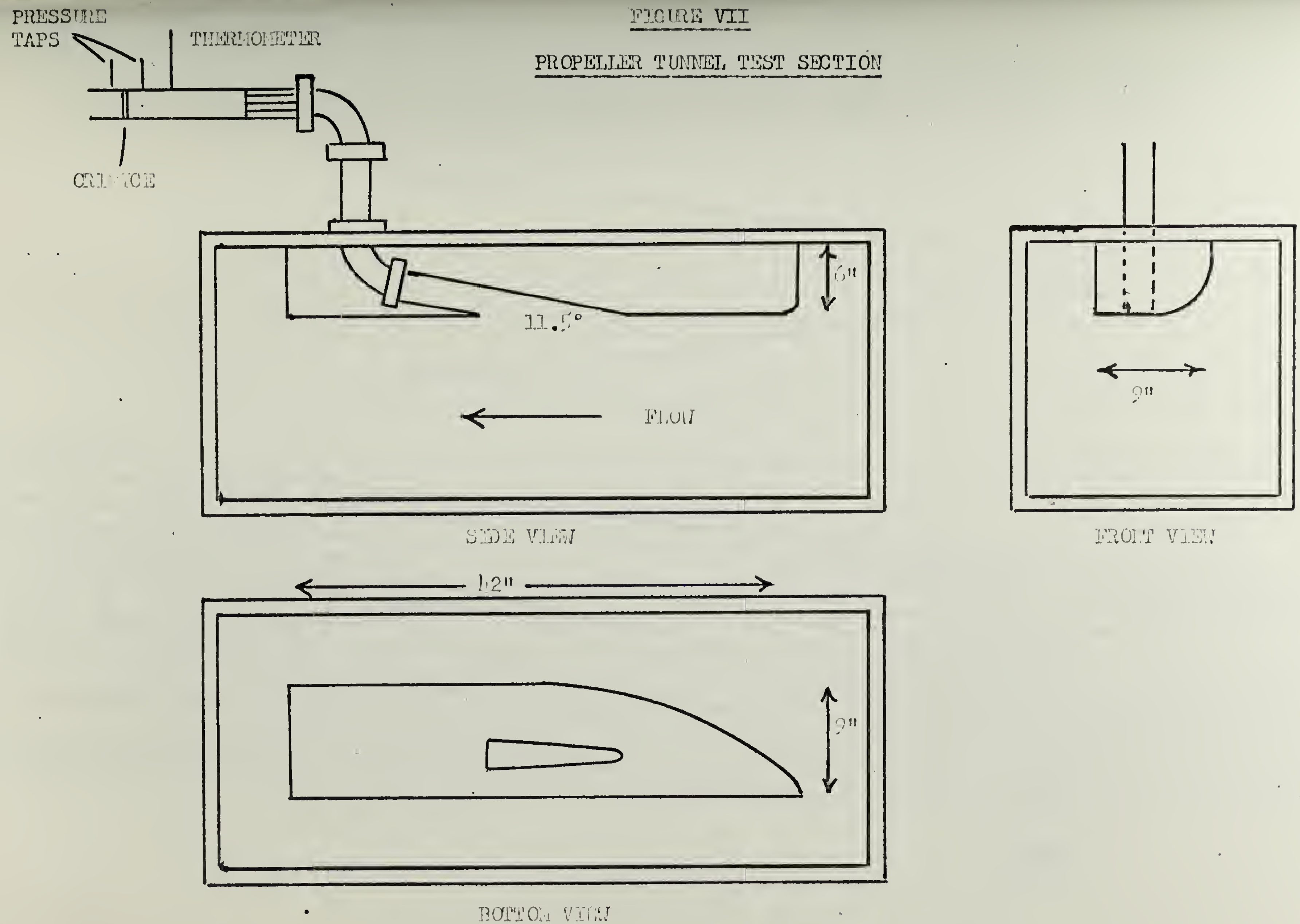
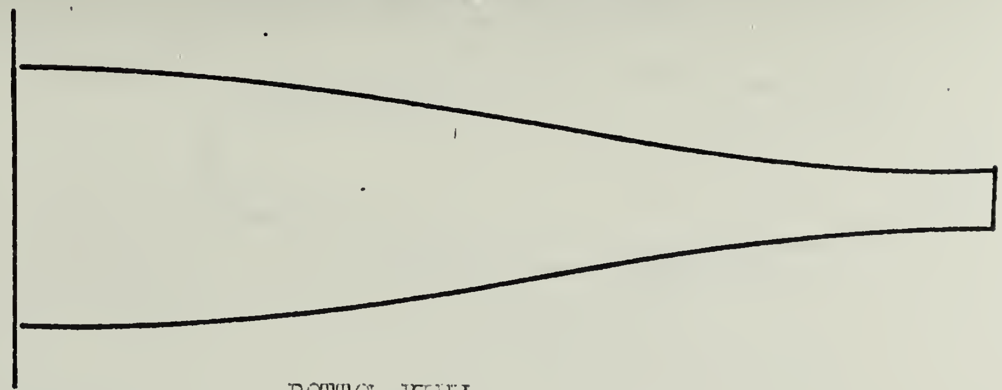
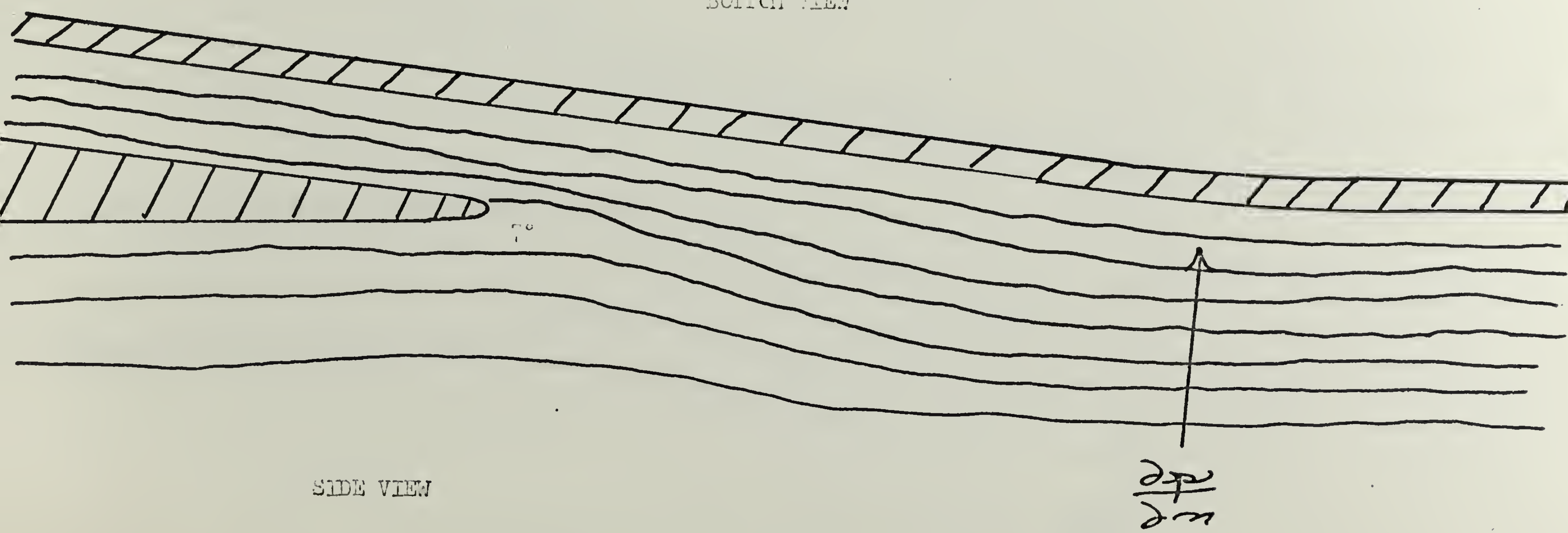


FIGURE VIII

HOSSMAN AND RANDALL'S INLET



BOTTOM VIEW



SIDE VIEW

FIGURE IX

FLOW AROUND A WATER-JET INLET

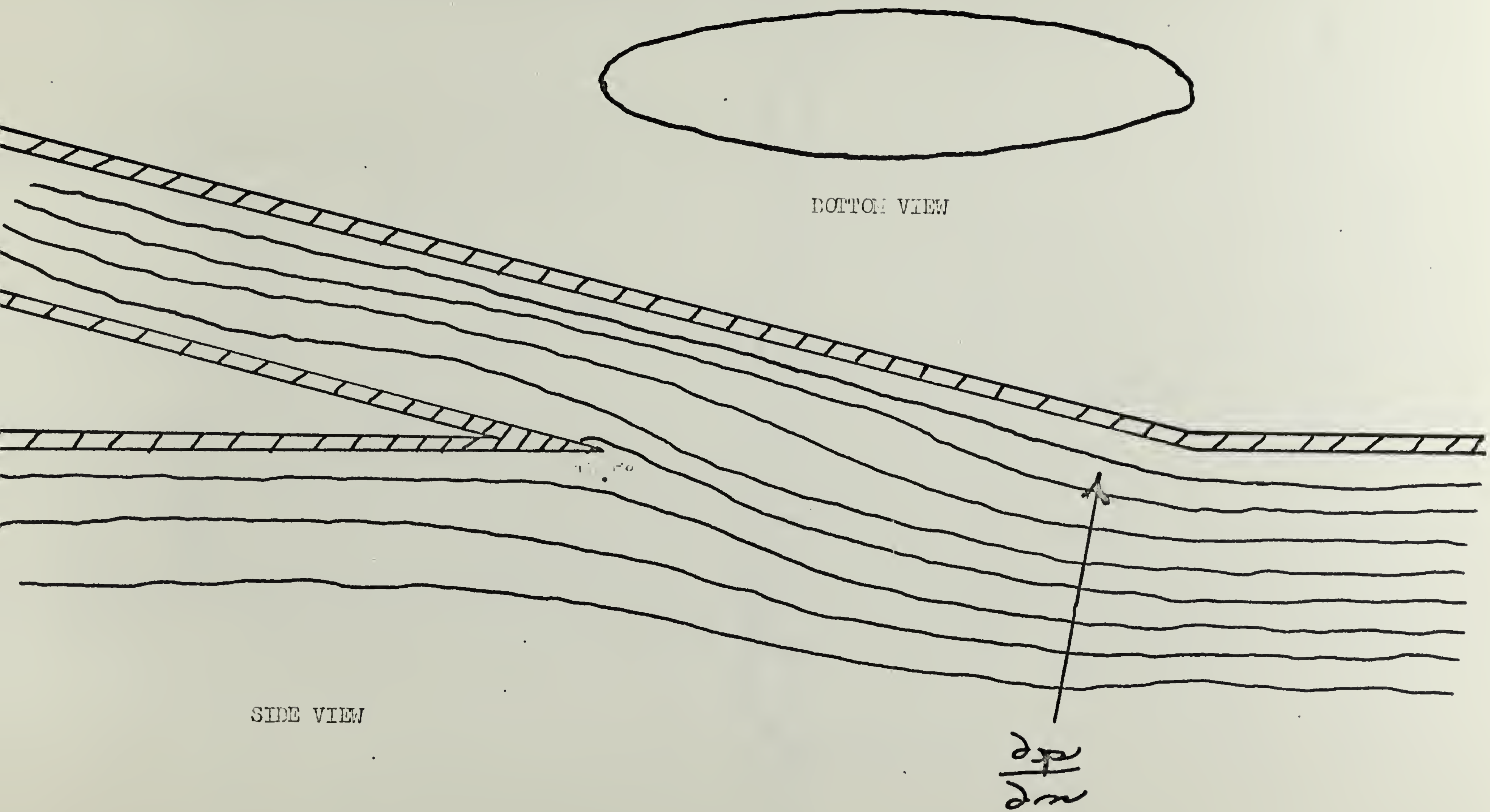


FIGURE X

CAPTURED AIR BUBBLE SHIP (SES)